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High-performance, in-plane switching liquid crystal device utilizing an optically isotropic liquid crystal blend of nanostructured liquid crystal droplets in a polymer matrix

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ABSTRACT

A light scatter-free, transparent, thermally stable, optically isotropic liquid crystal mixture was achieved among three different mixtures of liquid crystal E7: Norland Optical Adhesive 65 with concentrations 30:70, 40:60, and 50:50 wt%. The 50:50 wt% mixture exhibited the best performed optically isotropic state when exposed to ultraviolet light of intensity 150 mW/cm^2 for droplet formation. The high intensity ultraviolet light curing process induces nano-sized liquid crystal droplets in the polymer matrix of average droplet size 218 nm, characterized by scanning electron microscope. The analyzed result shows an excellent contrast ratio (CR) equal to 1574 at the normal direction and a high CR at a wide viewing angle. The magnitude of Kerr constant in these nano-sized PDLC was $\sim 7.36 \times 10^{-10}$ mV^{-2}, which was more than ~330 times that of a conventional Kerr material such as nitrobenzene. Unprecedented fast rising and falling times of approximately 385 μs and 1.1 ms, respectively, were achieved for the device. This high-performance material also eliminated the long-term hurdle of hysteresis to make it a promising candidate for next-generation display and photonic technologies.

1. Introduction

In the last 20 years, liquid crystal displays (LCDs) have been very successful in flat panel display markets due to phenomenal improvements in electro-optic (E-O) performance and reduction in production costs. In addition, the size of LCDs range from small mobile displays to large televisions helps to dominate it in the display market [1]. Requirement of an alignment layer increases the product cost and slows the response time of these displays. Fast response time is essential for three-dimensional LCD applications and field sequential color displays using red (R), green (G), and blue (B) light emitting diodes (LEDs) without noticeable color breakup [2]. Sequential RGB colors would eliminate the commonly used spatial color filters which in turn enhances light efficiency and resolution density by ~3×. Recent advancement of next-generation LCDs with a fast response time [3] and wide viewing angle without an alignment layer have been reported based on an optically isotropic LC (OILC) mixture, especially the blue phase liquid crystal (BPLC), which is optically isotropic in nature and have sub-millisecond order grey–grey response time. However, thermally stable polymer-stabilized blue phase (PSBP) suffers from high operating voltage and hysteresis [4–5]. Another novel, parallel approach for improving the response time without an alignment layer is to design nanostructured OILCs with polymer/LC blends. Haseba et al. produced an OILC via in situ photo polymerization by cross-linking monomers in the isotropic phase of a chiral nematic LC [6]. Recently, nano-sized, polymer-dispersed LC (PDLC) materials have been reported [7–8]. An ultraviolet (UV)-curable monomer was mixed with a nematic liquid crystal and cured under an appropriate intensity and wavelength of UV light. Droplet size can be controlled by the polymerization kinetics i.e. faster curing rate smaller liquid crystalline domains and vice versa [9–10]. The droplet size also depends on the polymer content, wherein increasing the polymer content domain size reduces beyond the limit of Rayleigh optical scattering so that the composites become optically isotropic [11]. The intent of this report is to investigate nanostructured PDLC, which is completely optically isotropic, scattering free and its E-O characteristics, such

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as voltage-dependent transmittance (*V*–*T*), hysteresis in *V*–*T*, response time, and viewing angle, under a two-domain in-plane switching (IPS) electrode [12–13].

2. Experimental

The precursors used for PDLC formation were a commercially-available eutectic nematic liquid crystal mixture E7 (Merck), UV light curable photopolymer (Norland Optical Adhesive 65, NOA-65), and photo initiator (Irgacure-651). The phase sequence of the E7 mixture was Crystalline −10 °C Nematic +61 °C Isotropic. E7 has a birefringence (Δn)=0.217 and dielectric anisotropy ($\Delta\varepsilon$)= +14.4. Although three different mixtures with different concentrations of LC: NOA-65 were prepared, 30:70, 40:60, and 50: 50 wt %, the 50:50 wt% mixture exhibited the best optically isotropic state. The mixture was heated to approximately 70 °C, which was sufficiently greater than the clearing temperature of E7, and then injected into a sandwich-type, two-domain IPS glass cell with a 2.7 μm gap. The electrode width (*w*) and electrode distance (l) were 3 μm and 7 μm, respectively. The cells were irradiated with a 365-nm UV light source for 1 min. The UV light intensity was optimized to produce the optimal OILC film. When the cell was exposed to an intensity of 150 mW/cm^2 for polymerization, it exhibited a more transparent state compared to the cell exposed to an intensity of 100 mW/cm^2.

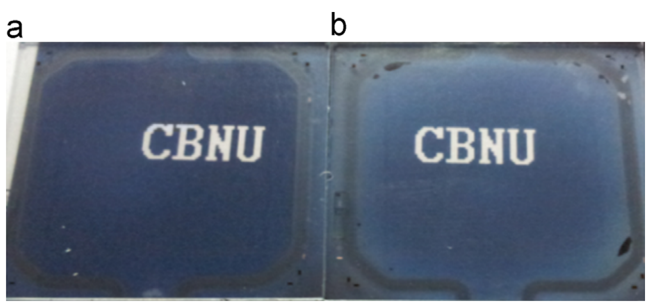

Fig. 1. Macroscopic images of the OILC cells under UV exposure. (a) High intensity (150 mW/cm^2) and (b) low intensity (100 mW/cm^2). The cell exposed weaker UV light shows noticeable light scattering such that the dark background looks sky-blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

Fig. 1(a) shows the cell exposed to a UV light intensity of 150 mW/cm^2 for droplet formation. The cell was placed above the "CBNU" phrase written on a dark paper. The cell showed a relatively clear black background without light scattering compared to the cell exposed to a UV light intensity of 100 mW/cm^2 (Fig. 1(b)), which exhibits significant light scattering due to the larger droplet, reducing the transparency of the cell. The Rayleigh-Gans (RG) approximation for light scattering in PDLC system assumes that light scattering is minimum if kD/2«1 for an incident wavelength λ, where $k=2\pi n_p/\lambda$ is the magnitude of the wave vector of the incident radiation inside the polymer matrix, and *D* is the diameter of the LC domain, [14]. Specifically, minimum scattering can be achieved when *D* is much smaller than λ. This model was appropriate for submicron-sized scattering particles and accurately describes the scattering properties of very small nematic droplets and small polymer crystallites. The average scattering cross-section was also related to the droplet size within the film via the following equation:.

$$\sigma_{avg} \propto \frac{D^6}{\lambda^4} \quad (1)$$

Our fabricated LC cell contains nano-sized droplets, so *D* is very small and fourth power of *D* is very very small, for that reason light scattering negligibly small. We have obtained excellent transparent OILC film due to above mentioned reason and the picture is shown in Fig. 1(a).

The textures of the cell were imaged using a polarizing optical microscopy (POM) system fitted with a Nikon DXM1200 digital camera. Temperature-dependent, electric field-induced optical switching was observed under POM by placing the cell inside a temperature controller (Linkam, TMS-94) and applying voltage using a waveform generator (Tektronix, AFG3022) connected to an

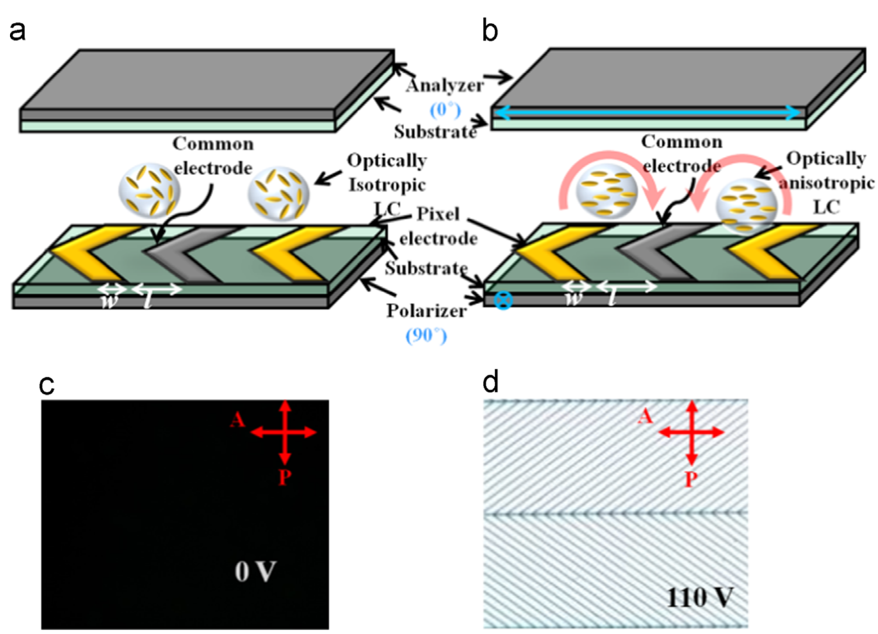

Fig. 2. Schematic diagram of the two-domain IPS cell. LCs are oriented randomly in nano-sized LC droplets in the "off" state (a), and LCs in the droplets reorient along the field direction in the "on" state (b). Actual POM textures of the cells during the "off" and "on" states are shown in (c) and (d), respectively.